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WATER-HOLDING CHARACTERISTICS OF WEATHERED GRANITIC ROCK

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ABSTRACT

Many chaparral and conifer species in California have root systems that penetrate to >6 m below the lower boundary of soil into fractured granite bedrock. Because soils in these ecosystems often are coarse-textured, shallow, and extremely dry during much of the year, the weathered rock is an important source of plant-available water. We measured the water retention characteristics of weathered granite rocks from the San Bernardino and San Jacinto Mountains to assess their capacity to hold plant-available water. Rock samples were segregated by weathering class (WC) ranging from WC 2 (very weakly weathered) to WC 6 (well weathered). After saturating the samples on a wet sand table, volumetric water contents (θ_v) at potentials to -1.5 MPa were determined using a pressure plate apparatus. Vapor equilibration was used to evaluate θ_v at -5.0 MPa. Available water capacity (AWC) was considered to be the water retained between matric potentials of -0.01 and -1.5 MPa. Rocks in WC 2-4 (cannot be broken by hand) had AWCs of about 1%, while rocks in WC 5 and 6 (can be broken in bare hands) had mean AWCs of 4 and 7%, respectively. Soils in the area have similar AWCs, but are usually <0.5 m thick, while the weathered rock mantle is often several meters thick. Thus the weathered rock is potentially a major source of water for chaparral and conifers, particularly during the summer dry season.

INTRODUCTION

The extensive chaparral and mixed conifer ecosystems in California must contend with a xeric soil moisture regime. Moisture accumulates in the soils and deeper substrates of these ecosystems during the cool, wet season (generally October-April) when rain and/or snow storms are common and evapotranspiration is minimal. During the dry season, vegetation undergoes severe stress because precipitation is minimal and competition is great for the available water stored within the substrate. Not only are these soils xeric, but they are often shallow and coarse-textured, particularly those on steep slopes, resulting in very low available water capacities (e.g., Ryan, 1991; Cohn and Retales, undated). On many such sites the chaparral and/or timber biomass is so disproportionately large for the soil available water capacities that it would be impossible to support the observed biomass through the dry season on the amount of water that can be stored within the soil.

Many chaparral and conifer species have root systems that penetrate far below the lower boundary of soil into the fractured bedrock. Hellmers et al. (1955) found that chamise (*Adenostoma fasciculatum* H. & A.) , Eastwood manzanita (*Arctostaphylos glandulosa* Eastw.), chaparral whitethorn (*Ceanothus leucodermis* Greene), toyon (*Heteromeles arbutifolia* M. Roem.), canyon oak (*Quercus chrysolepis* Liebm.), and California scrub oak (*Q. dumosa* Nutt.) had root systems which extended >8.5 m into rock substrates in the southern California mountains. The coarse roots of these species were typically compressed within the rock fractures they

followed, and finer cracks were often filled with mats of feeder roots. Organic material from the decomposition of roots was accumulated in some cracks.

Several studies have shown that weathered rock fragments are capable of holding water which may be available for plant use. Flint and Childs (1984) reported that volcanic and metasedimentary rock fragments from soils in Oregon had available water capacities of 6 to 18% (between -0.033 and -1.5 MPa[1] matric potentials). The effects of rock type and degree of weathering on available water capacity (AWC) were demonstrated, with increased AWC resulting from increased weathering (Flint and Childs, 1988). Hanson and Blevins (1979) also showed that rock type was an important factor in determining how much water was held. Sandstone fragments contained about 11% available water by volume while shale fragments contained about 23%. Newton et. al. (1988; personal communication, 1991) found that a large amount of water (up to 43% by volume) could be held by metasedimentary saprolite in Oregon. Douglas fir depleted an average of 2.8 cm of water from 90 cm of saprolitic rock, while ponderosa pine extracted 5.2 cm and manzanita removed 5.6 cm of water from the same saprolite thickness. Fine roots penetrated to depths below 165 cm in the weathered rock below, which typically began at a depth of 75 cm. Newton et al. (1988) concluded that a substantial amount of the water in the saprolite is gradually used by woody vegetation and that the amount used is plant species dependent.

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[1] NOTE: MPa x 10 = bars

Krammes (1969) determined that weathered granitic rock from the San Dimas Experimental Forest in the San Gabriel Mountains, southern California, had an average AWC (between -0.033 and -1.5 MPa potentials) of 9.6%. Arkley (1981) demonstrated that trees and brush in the San Bernardino Mountains of southern California rely on water extracted from considerable depths (>274 cm) in fractured or decomposed granitic rock when subject to summer drought.

It is clear that weathered rock material is an important source of water for vegetation during the summer dry season, yet little information is available on the water-holding characteristics of weathered rock in southern California. The objectives of this study were: (1) to evaluate the water-holding characteristics of weathered granitic rock, a lithology common in southern California chaparral and forest ecosystems, and (2) to develop a system for estimating the AWC of rocks based on their degree of weathering.

MATERIALS AND METHODS

Samples of weathered granitic rocks were obtained from two sites. Site SB is in the San Bernardino Mountains (NE1/4 NW1/4 sec. 12, T1N, R3W on Highway 330) at about 1250 m elevation and supports chaparral and conifer species, including canyon oak, chamise, ponderosa pine, and species of ceanothus and manzanita. Site SJ is in the San Jacinto Mountains (NW1/4 NE1/4 sec. 1, T4S, R1E on Highway 243) at about 1325 m elevation with dense chaparral consisting of chamise, canyon oak, manzanita, and ceanothus. In addition, several samples obtained from a third site located near Site SB were used for preliminary analyses.

Intact rock fragment samples were collected from road cuts after approximately 0.5 m of material was removed from the cut surface. The samples were classified according to the weathering classes developed for intrusive igneous rocks by Clayton and Arnold (1972) (Table 1). Weathering classes (WC) 1 and 7 were not found at the sampling sites, but WC 2 through 6 were collected from Site SB. Fewer samples were collected from Site SJ, and only from WC 4, 5, and 6. At Site SB samples were also taken of a massive silty clay loam material from a vein in the weathered granite. The size of the samples used in the analyses was usually 100 to 250 cm^3. Weathering classes 5 and 6 were trimmed to this size in the field, while WC 2 through 4 were trimmed in the lab using a diamond saw with water as the coolant. Samples of WC 6 were dipped in liquid Saran (200 g Saran L^{-1} methyl ethyl ketone) in the field to stabilize them for transport.

In the lab, all samples were coated with Saran for determination of bulk density and water retention (Soil Conservation Service [SCS], 1984). The volume of the rock was determined by Archimedes Principle. A 2 to 8 cm^2 patch of Saran was removed from a flat side of the rock and the exposed rock surface was pressed into laboratory tissue laid on a wet sand table. The rock was left to absorb water until it reached a constant weight, usually requiring about 2 weeks. It was then moved onto a pressure plate covered with a 1-cm-thick layer of silt loam, both which had been saturated with water. The exposed patch of rock was pressed into a laboratory tissue laid on the wet soil material. During the analysis it was critical to maintain contact between the rock, soil, and pressure plate. This became more of a problem at higher pressures (e.g., 1.5 MPa). It may help to mount the sample on the plate within a short cylinder of PVC pipe of the appropriate diameter and place a bag of lead shot (about 1.5 kg) on top of the sample (Klute, 1986).

The rock sample was equilibrated at different matric potentials in the pressure plate apparatus (Klute, 1986). We used -0.01 and -1.5 MPa as the limits for AWC, as suggested for coarse-textured, intact soil materials (Cassel and Nielsen, 1986). We recognized that the potentials which truly define "available water" can actually only be assessed *in situ* for any given material, and that they are plant species dependent. The values used in this study were chosen to provide an estimate of the AWC. Equilibration time for -0.01 MPa was typically 2 to 4 weeks, depending on weathering class, whereas equilibration at -1.5 MPa generally required 4 to 6 months. The long times required for equilibration were due to the large sample size,

which presented a long and tortuous path for water to travel within the rock. This factor probably contributed to the relatively frequent loss of matric contact between rocks and the soil layer on the pressure plate during the 1.5 MPa analysis. This situation would become evident only after about a week when the soil on the plate would be equilibrated under 1.5 MPa pressure and the plate outlet stopped dripping. The rocks would then be removed and found to have lost little or no weight beyond that recorded for the 0.01 MPa equilibration. They were then rewetted on the sand table to begin the process again.

The large sample size also meant that only about 6 samples could be mounted on each pressure plate. In retrospect, smaller samples, on the order of 75 to 100 cm^3, probably should be used to allow more samples to be analyzed at once, to decrease the length of time the samples remained on the plate, and to decrease the failure rate. It may also help to trim the samples to a tabular shape and remove Saran from most of one of the broad sides. This would increase the area of matric contact and decrease the travel distance for the matrix water.

Each rock sample was first equilibrated at the highest potential (-0.01 MPa), then weighed, rewetted, and equilibrated at a lower potential and weighed again. The process was repeated until the desired potentials had been evaluated.

After the pressure plate assessment at -1.5 MPa potential, several of the preliminary samples were equilbrated at -5.0 MPa potential without first rewetting. A vapor equilibration technique was used to achieve this low potential. This method consisted of

placing the samples in an atmosphere of known relative humidity established at constant temperature using water-salt solutions of known osmotic potential (Campbell and Gee, 1986). After a lengthy equilibration period, the sample is at the water potential of the osmotic solution. We placed the samples over 1.037 M KCl solutions in chambers stored in a constant (25 °C) temperature room to produce a potential of -5.0 MPa (according to the equation $\pi = C_s RT$, where π = osmotic pressure in MPa, C_s = concentration of solute in mol cm^{-3}, R = 8.2 MPa cm mol^{-1} $°K^{-1}$, T = °K (Gesser, 1974)). Sample weights were monitored for 3 months and the final weights were taken after 29 months. The large sample sizes made the equilibration process even slower than usual.

When the moisture tension evaluations were completed, each rock sample was oven dried (110 °C), and bulk density, volumetric water contents (θ_v), and AWCs were calculated (SCS, 1984). All weights and volumes were corrected for the Saran coating using measured densities of 1.30 g cm^{-3} for initial air-dry Saran, 0.90 g cm^{-3} for aged, moist Saran, and 0.75 g cm^{-3} for oven-dried Saran. Multiple comparisons of means was accomplished using one-way analysis of variance with Student-Newman-Keuls' test at the 0.05 probability level.

For mineralogical analyses, rock samples were crushed, composited, and quartered to obtain subsamples representative of each WC at each field site. The samples were powdered (<0.106 mm) and the kaolin content was determined on subsamples using a thermogravimetric analyzer and standards prepared from Halloysite no. 29 (Ward's Natural Science Establishment, Inc., Rochester, NY).

The <20-μm fraction of the powdered samples was separated by sedimentation, subsamples were K- and Mg-saturated and dried from water slurries on glass slides for x-ray diffraction (XRD) analysis using glycolation and heat treatments as described by Jackson (1979).

Abrasion pH was measured as an indicator of chemical weathering (Grant, 1969). Abrasion pH is the pH of the slurry resulting from grinding rock in distilled water. We placed 20 g of crushed (not powdered) rock in a corundum mortar with 40 ml distilled water and ground the rock with a pestle for 2.25 min. After the suspension settled for 2 min, the pH electrode was immersed in the suspension and equilibrated for 2.5 min, and the pH was recorded. Each WC was analyzed in triplicate.

Cation exchange capacity was measured on powdered (<0.106 mm) rock material using 1 M NaOAc buffered at pH 8.2 (SCS, 1984), and at pH 7.0. Rock fragments 2 to 5 mm in diameter were mounted on Al stubs, sputter coated with Au/Pd to a 30-nm thickness, and examined with a scanning electron microsope.

RESULTS AND DISCUSSION

Characteristics of the Weathered Rock

The weathered rock at Site SB was the most thoroughly described, sampled, and analyzed of the sites we investigated. It is representative of many of the weathered granitic rock sections exposed in the San Bernardino and San Jacinto Mountains. The rock is extensively jointed and the degree of weathering does not decrease uniformly with depth. Corestones of less weathered rock are surrounded by a more weathered rock matrix (WC 5 or 6) (Fig. 1). The rock typically has fractures 7 to 15 cm apart, corresponding to a very high fracuring density, as defined by Clayton and Arnold (1972). The fracture cracks were mostly 2 mm wide, but ranged from 1 to 20 mm wide.

Roots have exploited virtually all cracks, and typically are very fine to medium in size (<5 mm diam.), but some roots, particularly those of conifers, are much larger (Fig. 2). Very fine and fine roots have formed root mats in fractures of all orientations, as described by Hellmers (1955), and decomposed organic matter smelling of actinomycetes has accumulated in some cracks. Roots are limited to fracture cracks and were not observed to penetrate the matrix of the rock, even in rocks which otherwise met WC 6 criteria. Some weathered rock bodies are cut by veins of white, tan, or pale green fine-textured, friable material (Fig. 3). Such vein material is typically more densely exploited by roots than the surrounding weathered rock.

The rocks at both the SB and SJ sites are classified as granite (Ehlers and Blatt, 1982), and are medium-textured (quartz and feldspar grain size is 2 to 5 mm diam.) according to the classification scheme of Clayton and Arnold (1972). Mineral components of the <20-μm fraction of powdered rocks are shown in Table 2. The primary minerals in both SB and SJ rocks were quartz, feldspar, and biotite. Potassium-rich feldspar predominated in the SB rocks, while the SJ rocks contained Na-rich feldspar. Smectite and/or vermiculite, weathering products of biotite, were present in all weathering classes. The relative proportion of biotite generally decreased as WC increased. In the WC 6 rocks from Site SJ, biotite had apparently transformed completely to smectite and vermiculite. The fine-textured vein material consisted largely of quartz, kaolin, and smectite.

Small amounts of kaolin, a weathering product of feldspar, were detected in WC 2 through 5 at both sites (Table 2). The WC 6 rocks, particularly at Site SJ, contained substantially more kaolin. In the less weathered rocks, the feldspars show smooth, unpitted cleavage surfaces (Fig. 4a), but as they weather, micropits and kaolin deposits develop in the grains (Fig. 4b). Microporosity is increased by feldspar pitting, formation of clay- and silt-size kaolin, and the expansion and weathering of biotite books to produce vermiculite and smectite. These features produced by chemical weathering should therefore increase the water-holding capacity of the rocks.

Two chemical parameters, abrasion pH and CEC, were investigated to determine their usefulness as indicators of weathering class. Abrasion pH decreased with increased WC, with

the most pronounced decrease occurring between WC 5 and 6 (Table 2). Unfortunately, a single abrasion pH value cannot be assigned to indicate a corresponding weathering class because the original suite of primary minerals strongly influences the range of values obtained.

Cation exchange capacity increases slightly with increasing weathering class, since clay minerals have formed in the more weathered rocks (Table 2). The CEC values are low because quartz and feldspar are by far the most abundant minerals in the rocks and they contribute little to CEC. As with abrasion pH, specific CEC values do not correspond to specific weathering classes, because initial mineralogy strongly influences CEC.

Chemical weathering of feldspars and biotite is probably responsible for the small but progressive decreases in bulk density from WC 2 through 4 shown in Fig. 5. In WC 5 and 6, extensive development of intergranular microfractures, as well as increased microporosity from primary mineral dissolution and secondary mineral precipitation (e.g., Fig. 4), further reduces the density, as described by Clayton et al. (1979). Although the bulk densities of WC 5 and 6 varied more than those of the other weathering classes, they were typically in the range of 2.0 to 2.3 g cm^{-3}. The fine-textured vein material had a bulk density just under 2 g cm^{-3}.

Water Content at Various Matric Potentials

Water release curves showing θ_v as a function of matric potential (ψ_m) for representative samples of WC 2 through 6 are shown in Fig. 6. In WC 2 through 4, the release curves are relatively flat throughout, whereas the increased microporosity of WC 5 and 6

results in higher θ_v, particularly at low ψ_m, producing a steep initial portion of the curves. At ψ_m below -0.1 MPa the curves level off so that they are roughly parallel to each other.

The water release curves show that large decreases in ψ_m are necessary to extract even small amounts of water from rocks at $\psi_m <$ -0.1 MPa. However, even water held at ψ_m far lower than the -1.5 MPa depicted in Fig. 6 is available to some wildland plant species. For example, Poole and Miller (1975) found that deep-rooted chaparral species do not experience stomatal closure in response to water stress until plant water potentials drop below -3.5 to -4.5 MPa. The disposition of the total amount of water held in samples of WC 3, 4, and 6 is shown in Fig. 7. The water between 0 and -0.01 MPa is not held against gravitational forces and should drain freely from saturated material. The water held between -0.01 and -1.5 MPa is designated "available" water, while that held between -1.5 and -5.0 MPa is referred to as "slowly available" water. Water held below -5.0 MPa is "hygroscopic" water that is not available to plants, but was removed by oven drying at 110 °C. It is obvious from Fig. 7 that weathered rocks have the capacity to hold an appreciable amount of water that is either available or slowly available to plants. The samples for which data are presented in Fig. 7 show that the available and slowly available water capacities increase with increased weathering class.

Most θ_v data were collected at ψ_m of 0, -0.01 and -1.5 MPa. Mean θ_v values for the weathering classes at these ψ_m are presented in Fig. 8. For each of the weathering classes ≤ 4, the θ_v values decrease slightly as ψ_m decreases, but there are no significant

differences between means at the same ψ_m. However, the θ_v values for WC 5 and 6 are significantly greater than for WC ≤4 at each ψ_m, coinciding with the decrease in bulk density shown in Fig. 5. There are no significant differences in mean θ_v between WC 5 and 6 at the same ψ_m. The fine-textured vein material holds at least twice as much water as rock of any weathering class at a comparable ψ_m.

Available Water Capacity

The mean AWC values of the weathering classes are plotted in Fig. 9. Mean AWC is roughly constant at about 1% for WC 2 through 4, but increases to 4.2% in WC 5, and to 6.5% in WC 6. The vein material had a mean AWC of 6.1%. As indicated by the error bars in Fig. 9, AWC can vary considerably within a given weathering class. The vein material AWC was even more variable, but only 2 samples were analyzed. All AWC values for WC 2 through 4 fell within the range of 0.5 to 1.6%, but AWC for WC 5 ranged from 2.6 to 5.9%, and WC 6 ranged from 3.0 to 12.4% AWC. This variability may be attributed to incomplete equilibration of some samples at -1.5 MPa, as discussed in the Materials and Methods section, or to inherent differences in AWC.

Between-site variability was assessed for WC 5 and 6, since all WC 2 and 3 samples were from Site SB, and only one of the WC 4 samples was from Site SJ. The mean AWC values for WC 5 were not significantly different between Sites SB and SJ (Fig. 10). In contrast, the mean AWC for WC 6 at Site SJ was nearly double that at Site SB, which was not significantly different from the WC 5 means.

The higher AWC for WC 6 at Site SJ corresponds with a more advanced state of weathering than at Site SB. Biotite is more extensively altered to expansive phyllosilicates and the kaolin content is much higher in WC 6 rocks at Site SJ than at Site SB (Table 2). The observed differences in weathering between the sites may be due in part to differences in primary mineralogy, in that Na-feldspar, such as in the rock at Site SJ, is more readily weathered than K-feldspar (Goldich, 1938), which predominates at Site SB. Because weathering produces micropores that hold water, variations in the primary mineralogy and weathering susceptiblity have the potential to strongly influence water-holding characteristics in the higher weathering classes.

Bulk density differences coincide with the trends shown by AWC and mineralogy. The bulk densities of WC 5 at Site SB (2.25 g cm^{-3}) and Site SJ (2.27 g cm^{-3}), and WC 6 at Site SB (2.18 g cm^{-3}) are not significantly ($P = 0.05$) different, but all are significantly greater than the bulk density of WC 6 at Site SJ (1.99 g cm^{-3}). Increased AWC of the weathered rocks is correlated with decreasing bulk density ($r^2 = 0.73$) as shown in Fig. 11. This relationship is expected because lower bulk densities are the result of increased porosity. However, some of the pores in the more weathered rocks are sufficiently large so that they do not retain water at $\psi_m = -0.01$ MPa, thus accounting for the wider spread of points at the lower bulk densities.

IMPLICATIONS

The importance of the weathered rock mantle in southern California chaparral and forest ecosystems is apparent when considered relative to the soils. On the predominating steep (45 to 85%) slopes, colluvial movement is so rapid that soil development is severely inhibited (Graham et al., 1988) and the thin soil mantle is in transit past the shrubs and trees which are securely anchored in the weathered rock substrate. Soils in the study area are typically shallow Xeropsamments and Xerorthents which have AWCs of about 4 to 6% (Cohn and Retales, undated). These values match the AWCs we determined for WC 5 and 6 rocks, yet the soils are less than 0.5 m thick, while the weathered rock profiles are generally several meters thick. Thus, the weathered rock mantle is often capable of holding more plant-available water than the overlying soils. The weathered rock probably assumes a particularly important role in providing plant-available water during the summer dry season.

FIELD ESTIMATION OF AWC FOR WEATHERED GRANITE

One of the objectives of this study was to develop a system for estimating the AWC of rocks based on their degree of weathering. The information contained in Table 1 and Fig. 9 provide the basis for such a system, but several important factors must be kept in mind. First, the weathering class system in Table 1 is for intrusive igneous rocks only. Second, the AWC data in Fig. 9 is for medium-textured granite. There is substantial variability even within this relatively uniform lithology, and rocks with much different mineralogy or texture may have quite different AWCs for a given weathering class. Finally, many chaparral and conifer species can extract water from substrates at potentials far lower than -1.5 MPa, so our estimates of AWC are conservative from a wildlands persective. These considerations should be recognized when using the information in this report for field assessment of AWC.

The first step in making a field evaluation of AWC of granitic rock is to identify the weathering classes present and the proportion of each class in the rock profile. The depth range to be considered begins at the paralithic or lithic contact and extends as deep as roots are observed or estimated to penetrate. The most serious obstacle is finding an exposure deep enough to observe the rock profile in the vicinity of interest. Road cuts may be the exposures most readily available, but care should be taken to use a cut representative of the site being evaluated. Cuts into ridges often expose rock that is less weathered than rock under other parts of the landscape. Ridges may be high points in the landscape because the underlying rock is

inherently more resistent, but the water-shedding hydrologic regime of ridges also creates a drier environment which inhibits weathering. If a road cut or other pre-existing exposure is used, the face should be dug back into the rock to obtain samples for evaluation. Granitic rock material can weather rapidly when exposed to surface conditions in road cuts.

If no large exposure is available, the saprolite may be dug or augered. We did not test how the different weathering classes respond to the spade and auger, but some correlation is likley. For example, it is doubtful that these tools would effectively penetrate rocks of WC ≤4. In any case, the heterogeneity typical of granite weathering profiles (e.g., corestones) should be recognized, and accounted for if possible.

The actual determination of weathering classes is relatively simple using the criteria developed by Clayton and Arnold (1972) (Table 1). The total thickness of each weathering class in the rock profile can then be multiplied by the appropriate AWC value (expressed in fractional form; e.g., 7% = 0.07) from the following list.

Weathering Class	AWC
2-4	0.01
5	0.04
6	0.07

The values obtained for each weathering class are summed to give the total available water that can be held by the profile. For example, consider a rock profile 300 cm thick composed of WC 2

corestones that sum to 75 cm thickness, set in a matrix of WC 6 saprolite. The available water in the WC 2 rock is 0.75 cm (0.01 x 75 cm) and in the WC 6 rock it is 15.75 cm (0.07 x 225 cm), for a profile total of 16.5 cm.

Vein materials with the same texture as those analyzed in this study may be assigned the mean value of 6%. Perhaps a better approach for these fine-textured materials is to use AWC estimation guides developed for soils of the same textural class.

AREAS FOR FUTURE INVESTIGATION

This study has shown that weathered granite can hold a substantial amount of plant-available water. However, very little is known about the overall importance of weathered rock substrates in ecosystems. The following lines of investigation are suggested to promote a better understanding of this virtually ignored substrate.

1. More field observations and descriptions of various kinds of weathered rock profiles are needed. In this respect, Forest Service soil scientists and other earth scientists can make a very valuable contribution toward understanding the importance of rock substrates. Unfortunately, standard description procedures for rock profiles do not exist. The publication by Clayton and Arnold (1972) offers a good system to begin with, which includes description of grain size, fracturing density, and weathering. Descriptions should also include root distribution and size. Accompanying information on the overlying soil and vegetation (e.g., species, biomass, timber site productivity) would be very helpful in assessing the relative importance of the rock substrate.

2. More analyses of different kinds of intrusive igneous rocks (granodiorite, diorite, etc., with different textures) would result in an AWC evaluation guide of wider applicability, but still based on Clayton and Arnold's weathering class scheme.

3. Classification schemes for sedimentary, metamorphic, and volcanic rocks are needed, and AWC data need to be generated for the various classes.

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Table 1. Weathering classes of intrusive igneous rocks according to Clayton and Arnold (1972).

Class 1, Unweathered Rock:	Unweathered rock will ring from a hammer blow; cannot be dug by the point of a rock hammer; joint sets are the only visible fractures; no iron stains emanate from biotites; joint sets are distinct and angular; biotites are black and compact; feldspars appear to be clear and fresh.
Class 2, Very Weakly Weathered Rock:	Very weakly weathered rock is similar to Class 1, except for visible iron stains that emanate from biotites; biotites may also appear "expanded" when viewed through a hand lens; feldspars may show some opacity; joint sets are distinct and angular.
Class 3, Weakly Weathered Rock:	Weakly weathered rock gives a dull ring from a hammer blow; can be broken into "hand-sized" rocks with moderate difficulty using a hammer; feldspars are opaque and milky; no root penetration; joint sets are subangular.
Class 4, Moderately Weathered Rock:	Moderately weathered rock may be weakly spalling. Except for the spall rind, if present, rock cannot be broken by hand; no ring or dull ring from hammer blow; feldspars are opaque and milky; biotites usually have a golden yellow sheen; joint sets indistinct and rounded to subangular.
Class 5, Moderately Well Weathered Rock:	Moderately well weathered rock will break into small fragments or sheets under moderate pressure from bare hands; usually spalling; root penetration limited to fractures, unlike Class 6 rock where roots penetrate through the rock matrix; joint sets are weakly visible and rounded; feldspars are powdery; biotites have a light golden sheen.
Class 6, Well Weathered Rock:	Well-weathered rock can be broken by hand into sand-sized particles (grus); usually so weathered that it is difficult to determine if rock is spalling, roots can penetrate between grains; only major joints are preserved and filled with grus; feldspars are powdery; biotites may appear silver or white in thin flakes.
Class 7, Very Well Weathered Rock:	Very well weathered rock has feldspars that have weathered to clay minerals and rock is plastic when wet, no resistance to roots.

Table 2. Mineral components and indicators of chemical weathering for the weathering classes sampled at sites SB and SJ.

Site	WC	Mineral components[†]	Kaolin	Abrasion pH	CEC pH 7	CEC pH 8.2
			%		----$cmol_c$ kg^{-1}-----	
SB	2	F+++, Q+++, B++, S++, K+	1	7.98	1.4	2.0
	3	F+++, Q+++, B+, S+, K+	1	7.90	1.6	2.3
	4	F+++, Q+++, B+, S+, K+	1	7.90	1.2	1.7
	5	F+++, Q+++, S+, K+, B+	2	7.45	1.6	2.4
	6	F+++, Q+++, K++, S+, B+	4	6.93	2.0	3.3
	VM[‡]	Q+++, K+++, S+++, F+	39	nd[§]	nd	nd
SJ	2	Q+++, F+++, B++, V+, S+, K+	2	8.69	2.8	3.1
	3	Q+++, F+++, B++, V+, S+, K+	2	8.38	3.4	4.4
	4	Q+++, F+++, B++, S+, V+, K+	2	8.10	3.3	4.8
	5	Q+++, F+++, B++, S+, V+, K+	2	8.07	3.4	5.7
	6	Q+++, F+++, K++, S+, V+	12	7.38	5.2	9.7

[†] Determined by X-ray diffraction of the <20-μm fraction of powdered rocks. B = biotite, F = feldspar, K = kaolin, Q = quartz, S = smectite, V = vermiculite. Minerals are listed in order of estimated abundance: + = <5%, ++ = 5-10%, +++ = 10-50%

[‡] VM = silty clay loam vein material

[§] nd = not determined

Fig. 1. Weathered granite profiles, such as this exposure at Site SB, typically have corestones of less weathered rock set in a more highly weathered matrix. Note roots in cavity where corestone has been removed (lower right). Shovel is 70 cm long.

Fig. 2. Roots, ranging in size from <1 mm to over 10 cm in diameter, occupy virtually all cracks in the extensively fractured granite at Site SB. Shovel is 70 cm long.

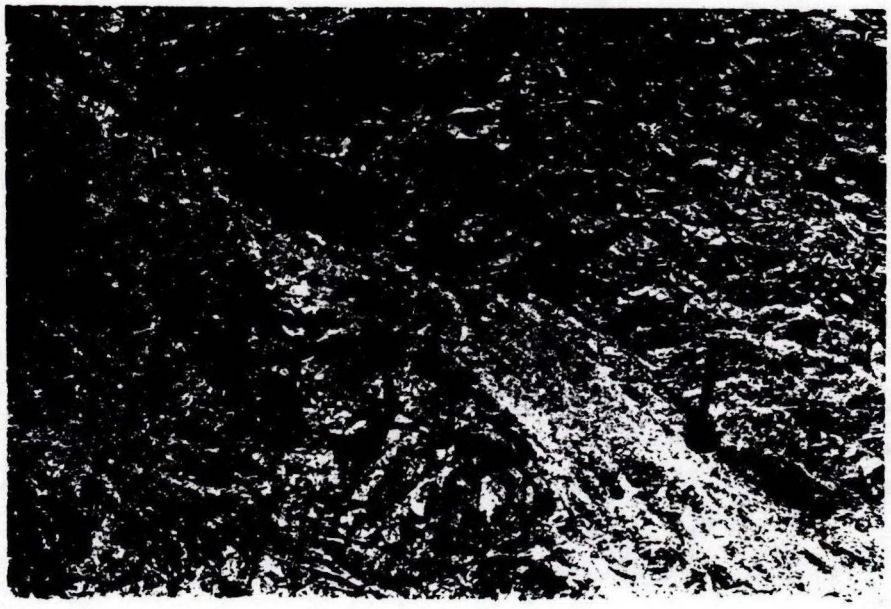

Fig. 3. Some weathered rock profiles are cut by veins of fine-textured material that is more densely exploited by roots than the surrounding rock. Samples designated "VM" were taken from this vein at Site SB. Shovel is 70 cm long.

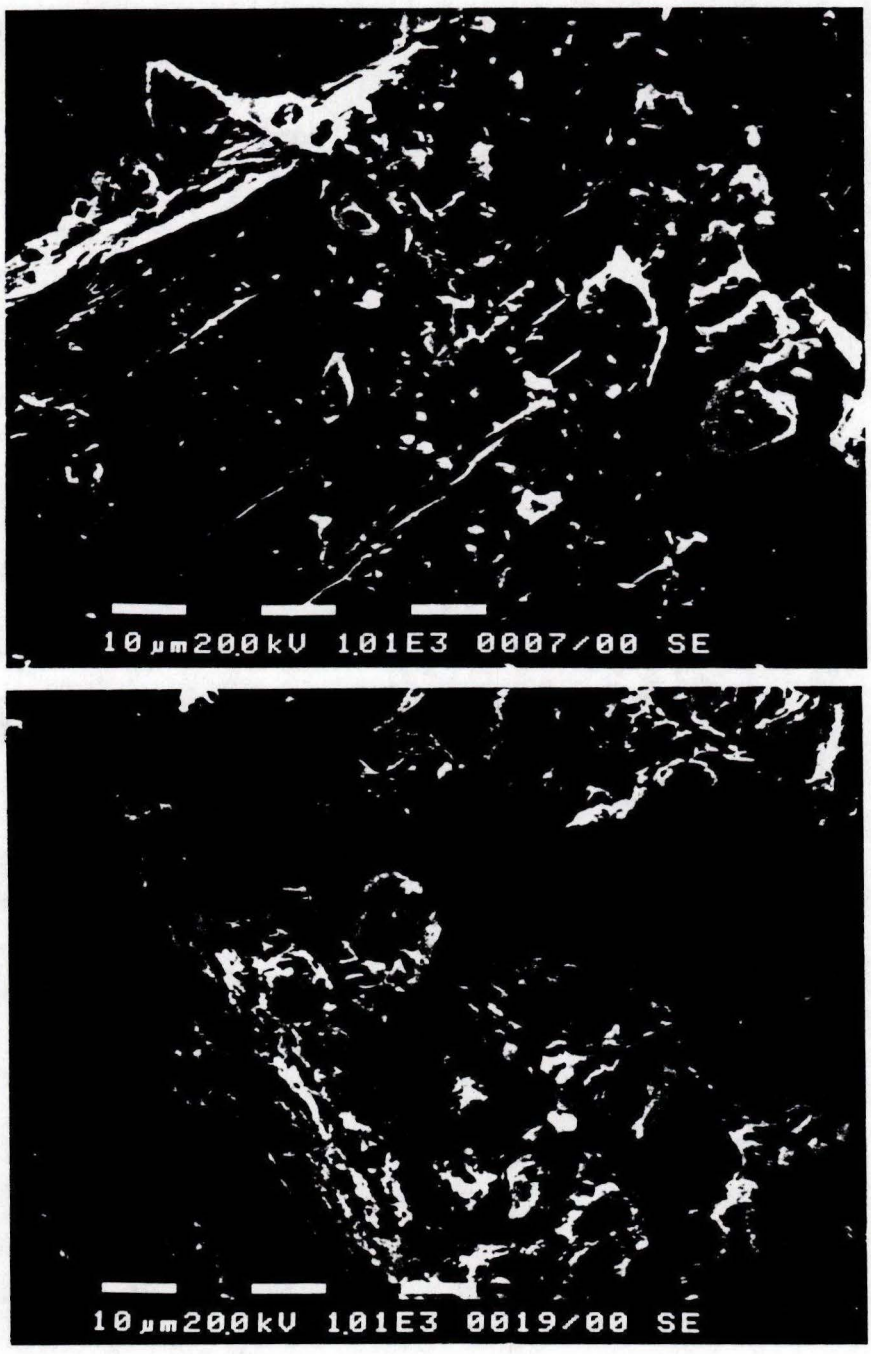

Fig. 4. Scanning electron micrographs showing (a) the smooth surface of a feldspar grain in WC 2 rock; and (b) a pitted feldspar surface with adhering kaolin clay in a WC 6 rock. White bars are 10 µm long.

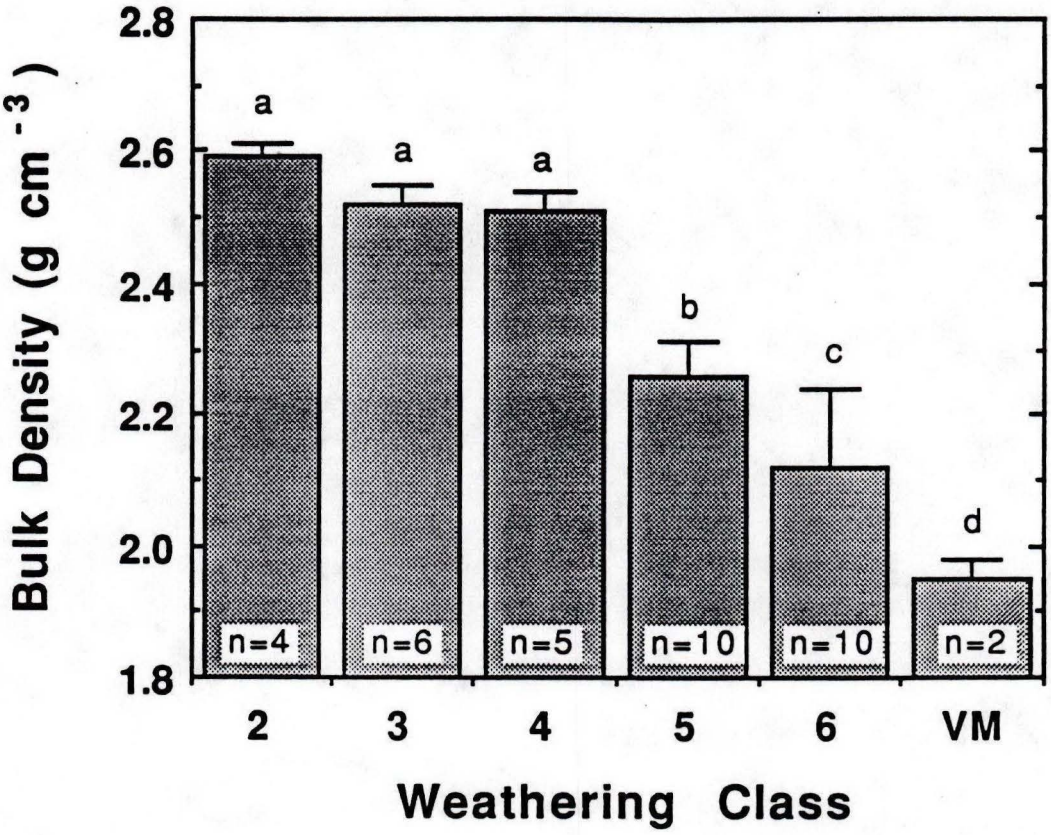

Fig. 5. Mean bulk density for each weathering class. Error bars indicate one standard deviation, n = number of samples for each class, and similar letters above bars indicate no significant (P = 0.05) difference between means. VM = vein material.

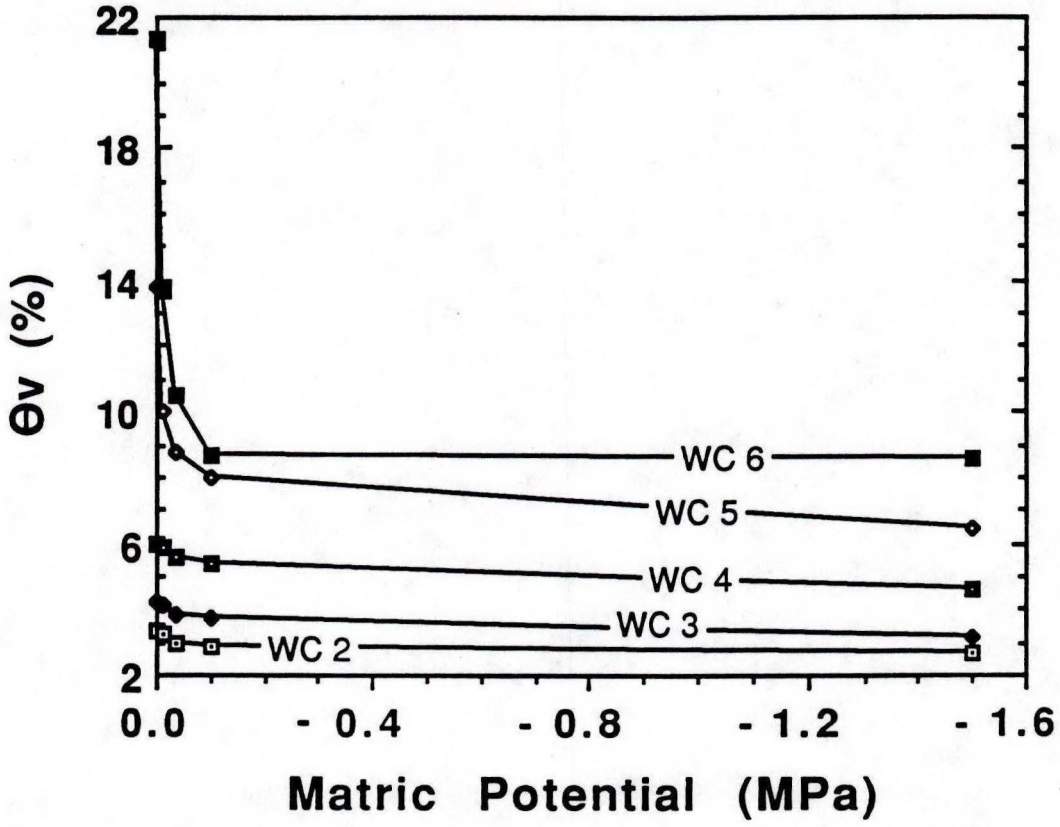

Fig. 6. Volumetric water content (θv) as a function of matric potential for representative samples.

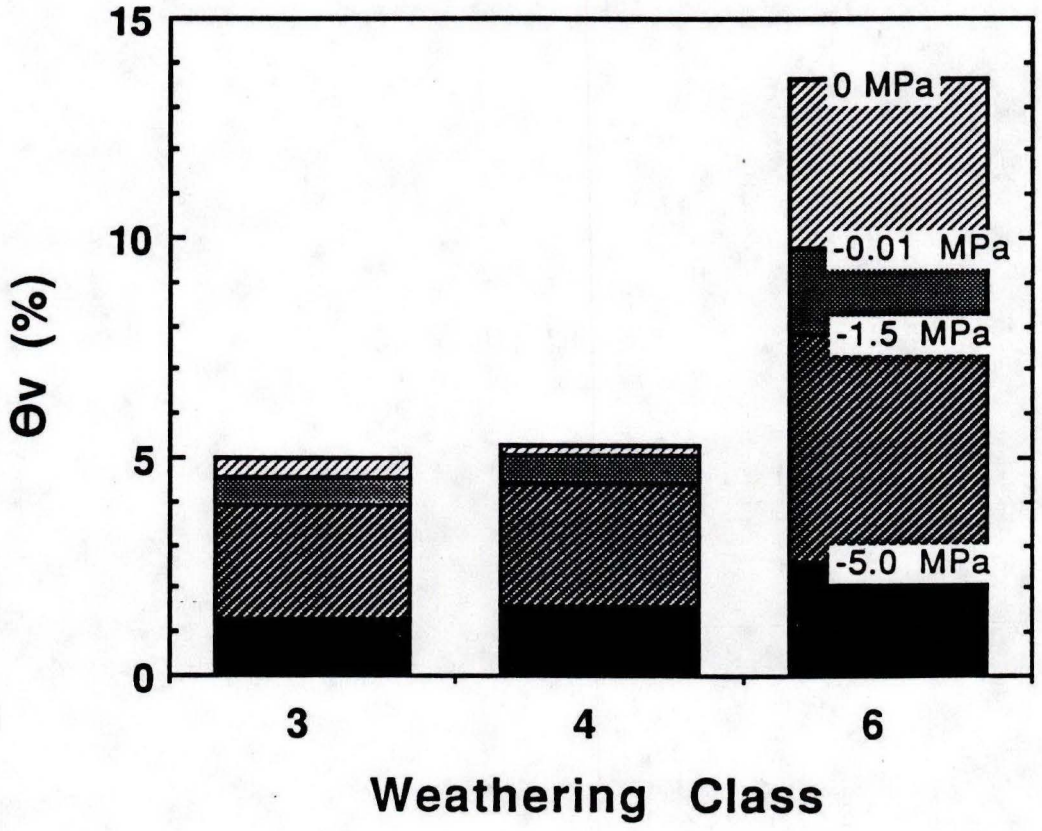

Fig. 7. Volumetric water content (θv) held at various matric potentials for samples of WC 3, 4, and 6.

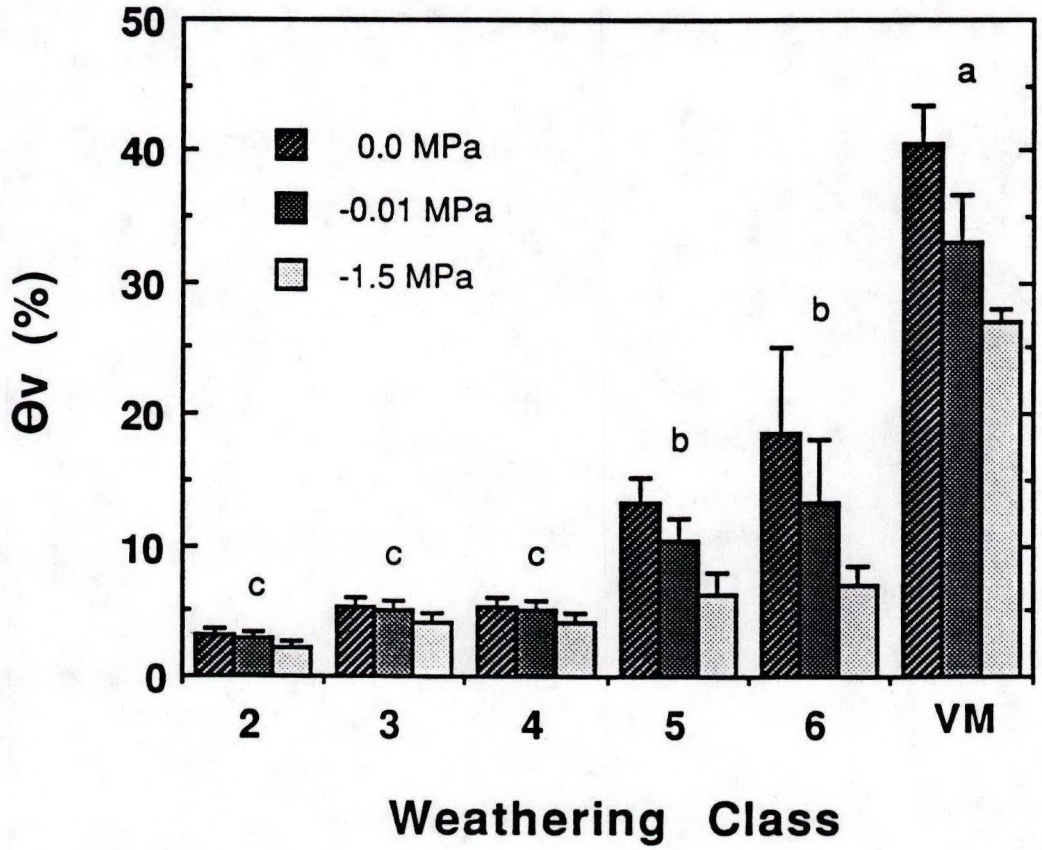

Fig. 8. Mean volumetric water contents (θv) of the weathering classes at matric potentials of 0, -0.01, and -1.5 MPa. Error bars indicate one standard deviation. Weathering classes with the same letters do not have significant (P = 0.05) differences in mean θv at the same matric potential. VM = vein material.

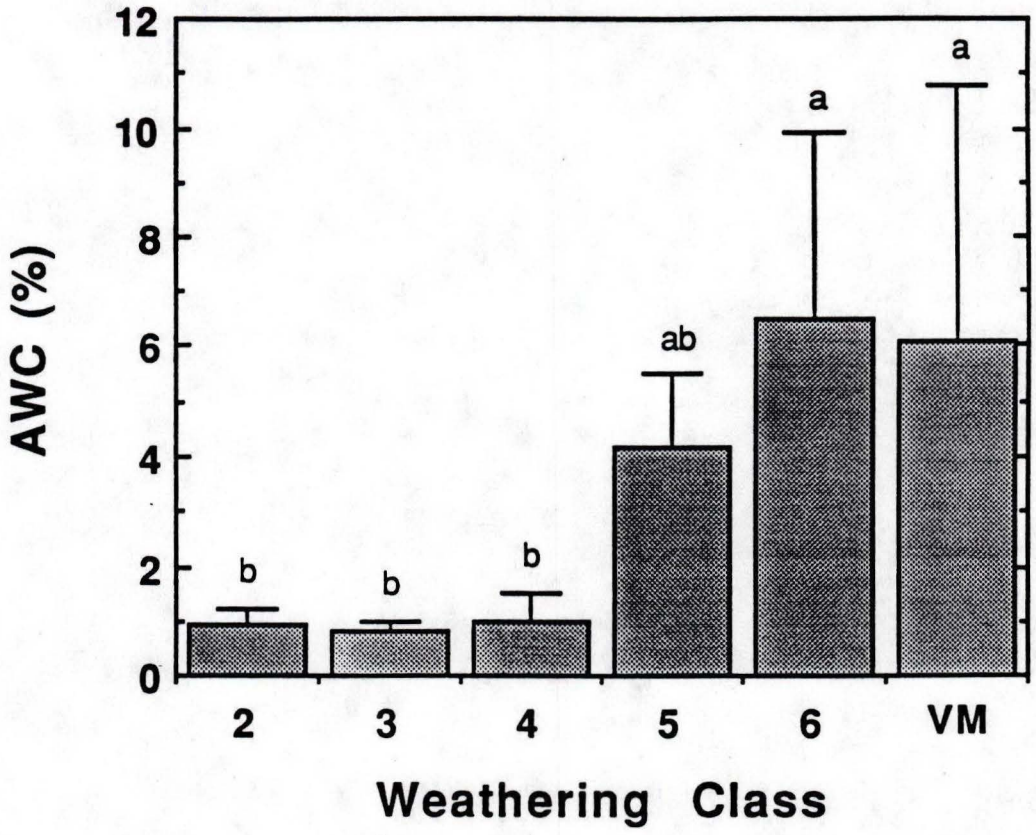

Fig. 9. Mean available water capacity (AWC) for the weathering classes. Error bars indicate one standard deviation. Similar letters above bars indicate no significant (P = 0.05) difference between means. VM = vein material.

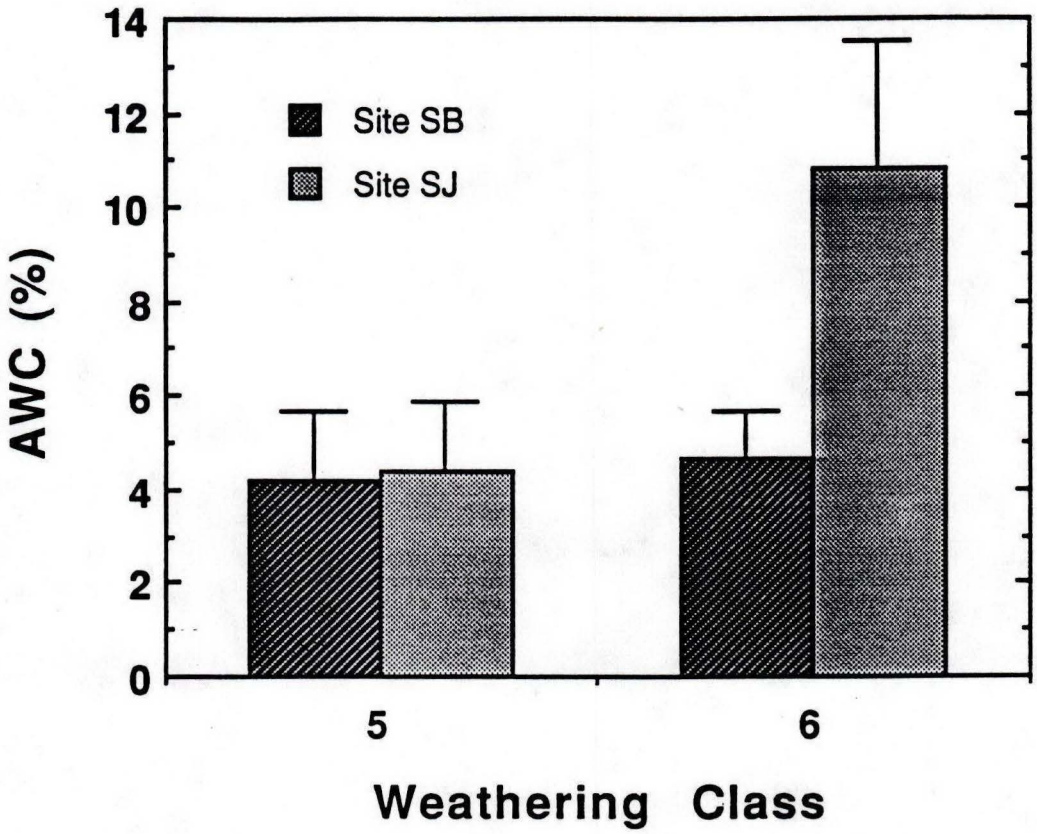

Fig. 10. Mean available water capacity (AWC) for weathering classes 5 and 6 by site. Error bars indicate one standard deviation. For both weathering classes, seven Site SB samples and three Site SJ samples were analyzed.

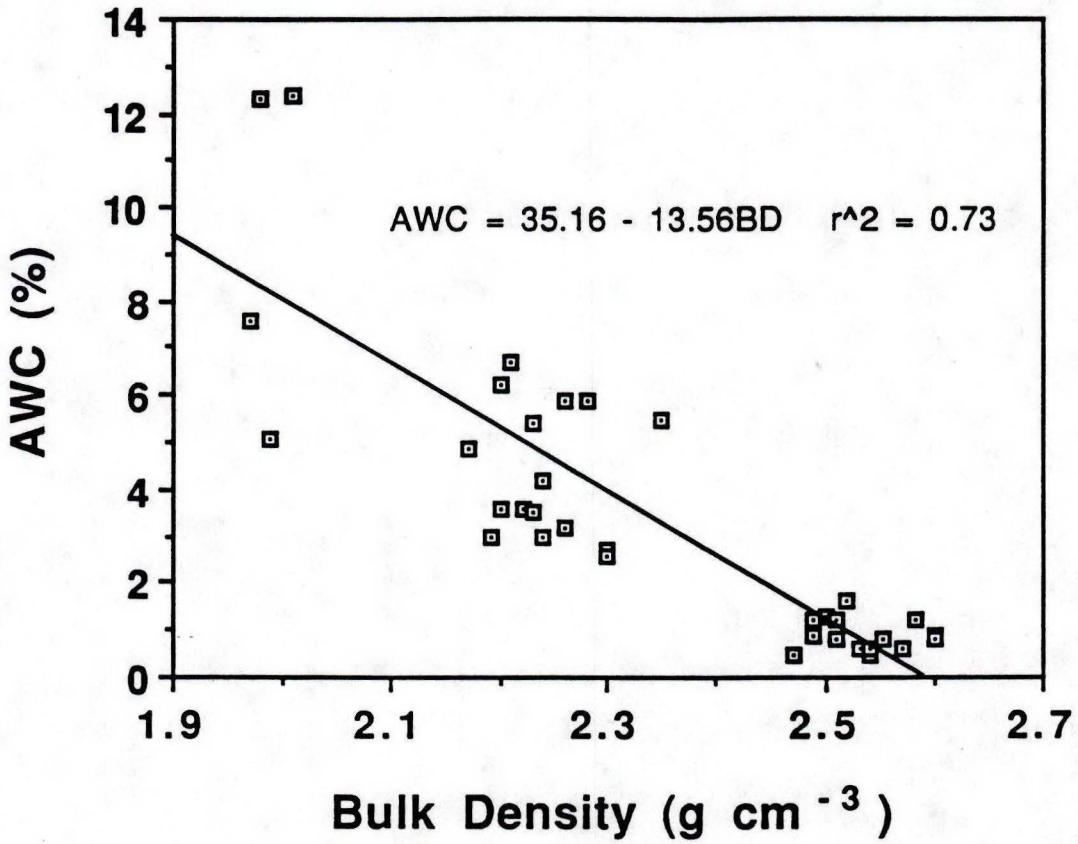

Fig. 11. Relationship between bulk density and available water capacity (AWC).

APPENDIX I. Complete bulk density, volumetric water content (θ_v), and available water capacity (AWC) data for the analyzed rock samples.

Site	Weathering class	Bulk density	θ_v 0 MPa	-0.01 MPa	-0.033 MPa	-0.10 MPa	-1.5 MPa	AWC
		g cm^{-3}	%					
SB	2	2.58	3.6	3.6	3.2	3.2	2.4	1.2
		2.60	2.5	2.5	2.2	2.2	1.7	0.8
		2.60	2.9	2.8	2.6	2.6	1.9	0.9
		2.57	3.4	3.3	3.0	2.9	2.7	0.6
	$\bar{x} \pm$ SD	2.59±0.02	3.1±0.5	3.1±0.5	2.8±0.4	2.7±0.4	2.2±0.5	0.9±0.3
	3	2.49	6.4	6.1	5.8	5.7	5.0	1.2
		2.54	4.7	4.5	4.4	4.2	4.0	0.5
		2.53	4.8	4.6	4.4	4.0	4.0	0.6
		2.51	5.0	5.1	4.4	4.3	4.3	0.8
		2.55	4.2	4.1	3.8	3.7	3.2	0.8
		2.49	5.9	5.4	5.4	5.0	4.6	0.9
	$\bar{x} \pm$ SD	2.52±0.03	5.2±0.8	5.0±0.7	4.7±0.7	4.5±0.7	4.2±0.6	0.8±0.2
	4	2.50	6.0	5.9	5.6	5.4	4.6	1.3
		2.47	6.0	5.5	5.4	5.2	4.9	0.5
		2.54	4.8	4.6	4.3	4.2	4.0	0.6
		2.52	4.9	4.6	4.4	4.0	3.1	1.6
	$\bar{x} \pm$ SD	2.51±0.03	5.4±0.7	5.2±0.7	4.9±0.7	4.7±0.7	4.2±0.8	1.0±0.5

APPENDIX I. (continued)

Site	Weathering class	Bulk density	θ_v 0 MPa	-0.01 MPa	-0.033 MPa	-0.10 MPa	-1.5 MPa	AWC
		g cm^{-3}	%					
SB	5	2.23	13.3	9.8	8.6	7.0	4.3	5.4
		2.22	13.8	10.0	8.8	8.0	6.4	3.6
		2.19	14.2	10.5	9.7	8.6	7.5	3.0
		2.26	13.0	11.0	9.7	8.1	5.1	5.9
		2.28	12.2	10.8	9.4	7.4	4.9	5.9
		2.30	10.9	8.8	7.8	6.8	6.2	2.6
		2.30	10.1	7.4	6.4	5.5	4.7	2.7
	$\bar{x} \pm$ SD	2.25±0.04	12.5±1.5	9.8±1.3	8.6±1.2	7.3±1.0	5.6±1.1	4.2±1.5
SB	6	1.99	21.3	13.7	10.5	8.7	8.6	5.1
		2.26	11.7	8.2	-	-	5.0	3.2
		2.24	11.8	8.0	-	-	5.0	3.0
		2.17	16.3	11.5	-	-	6.6	4.9
		2.20	15.1	12.0	-	-	5.8	6.2
		2.21	13.6	13.3	-	-	6.6	6.7
		2.20	14.2	9.4	-	-	5.8	3.6
	$\bar{x} \pm$ SD	2.18±0.09	14.9±3.3	10.9±2.3			6.2±1.2	4.7±1.5
	VM	1.93	42.5	35.7	-	-	26.3	9.4
		1.97	38.4	30.5	-	-	27.7	2.8
	$\bar{x} \pm$ SD	1.95±0.03	40.5±2.9	33.1±3.7			27.0±1.0	6.1±4.7

APPENDIX I. (continued)

Site	Weathering class	Bulk density	θ_v 0 MPa	-0.01 MPa	-0.033 MPa	-0.10 MPa	-1.5 MPa	AWC
		g cm^{-3}			%			
SJ	4	2.51	-	5.1	-	-	3.9	1.2
	5	2.24	16.2	13.0	-	-	8.8	4.2
		2.23	16.1	12.1	-	-	8.6	3.5
		2.35	12.9	11.7	-	-	6.2	5.5
	$\bar{x} \pm$ SD	2.27±0.07	15.1±1.9	12.3±0.7			7.9±1.4	4.4±1.0
	6	1.97	22.8	14.8	-	-	7.2	7.6
		1.98	30.2	21.5	-	-	9.2	12.3
		2.01	28.1	21.2	-	-	8.8	12.4
	$\bar{x} \pm$ SD	1.99±0.02	27.0±3.8	19.2±3.8			8.4±1.1	10.8±2.7